Wavefront Sensing and Optical Control Studies

"Fine Figure Control"

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Abstract

We discuss and show results of a phase retrieval based heirarchical optical control loop for *fine figure control* of segmented aperture optical systems. We address the needs of DCATT and NGST.

Viewgraphs will be available at http://jansky.gsfc.nasa.gov/OSCAR

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key
DONE
IN-PROGRESS
TO BE/SHOULD BE DONE

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Purpose of Study

What is the "best" Wavefront Sensing and Optical Control Method for Segmented Aperture Telescopes ?

- **Determine Effects of:**
  - **Calibration**
  - **Sampling, finite pixel size,**
  - **jitter, noise, diamond turning**
  - **Spectral bandpass, Defocus range,**
  - **detector MTF, scatter etc...**

- **Comparative Wavefront Sensing**
  - **Compare Phase Ret/Div,**
  - **Shack-Hartmann,**
  - **Interferometry**

- **Parameterize effects with respect to:**
  - **Dynamic Range and Resolution**
  - **Accuracy/Precision**
  - **Sensitivity**
  - **Bandwidth of correction**
  - **Computational complexity**
  - **Robustness**
  - **Spatial Frequency Content**
  - **Convergence (Multiple start pts.)**
  - **Stability**
  - **Phase Retrieval/Diversity Algorithms**
  - **Control Law Algorithms**

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Optical Modelling

- Simulations “tuned” to DCATT
- includes:
  - Full-Aperture Zernikes /Sub-Aperture Zernikes, {0 - 2.5λ rms}.
  - 90.3 cm aperture, 21% obscured, 7 hex segments.
  - Residual Polish Marks / Random power law surfs.
  - Polychromatic PSFs, {λ=0.6328 um, $\Delta\lambda$=10nm}.
  - System Jitter, {0 - 1.5 pixels rms}.
  - Pixelization {9 um pixels}.
  - read noise {13 electrons rms}.
  - photon noise.
  - full-well {80,000 e}.
  - quantization {12 bit = 4096}.
  - Actuator Influence functions (Xinetics 349 DM)

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Example of LEO System Control File

Keywords for:

- Pupil diameters, wavelengths, bandpass,
- pixelization, obscuration ratio,
- full aperture Zernikes, spiders, pads,
- aper rotation with respect to CCD line/scan
- jitter in x and y directions,
- PM and SM secondary mirror mid-spatial
- random high spatial freqencies
- detector dynamic range, shot noise,
- readnoise, quantization, finite pixel size.
- actuator input files, influence functions

```
=      aper_22.in         # Aperture control file (set to "none" if not using).
=      0.903              # Exit pupil Diameter (meters)  (system is F/15)
=      0.6328             # Wavelength (microns)
=      0.1330311          # Output Sample spacing (arseconds) (pixels are 9 um)
=      Y                  # Generate PRF (Y or N)
=      0.1330311          # Detector element size for PRF (arseconds)
Npsf=  7                  # Number of PSF's across Passband.
fwhm=  0.0100             # FWHM of Filter (microns) (if Npsf's > 1 )
=      0.21384            # aperture obscuration ratio (0.21384)
Ztype= 1                  # Zernike type (0 = Annular, 1 = Code 5)
 Z01=  -0.051605          # Piston (microns WFE )
 Z02=   0.014292          # X-tilt (microns WFE )
 Z03=   0.121884          # Y-tilt (microns WFE )
 Z04=   0.012207          # X-Y astigmatism (microns WFE )
 Z05=   0.121851          # Focus (microns WFE )
 Z06=   0.164621          # 45-degree (microns WFE )
 Z07=   0.187863          # Trefoil (microns WFE )
 Z08=   0.012174          # X-coma (microns WFE )
 Z09=  -0.110907          # Y-coma(microns WFE )
 Z10=  -0.090205          # Trefoil (microns WFE )
 Z11=  -0.126233          # (microns WFE )
 Z12=   0.227831          # (microns WFE )
 Z13=   0.078349          # Fourth-order spherical (microns WFE )
 Z14=  -0.084945          # (microns WFE )
            .
            .
Z32=  -0.144799           # (microns WFE )
=      N                  # Are OTA SMA spiders present? (Y or N)
=      N                  # Are OTA PMA pads present? (Y or N)
=      0.000000           # OTA aperture rotation angle (degrees)
=      0.000000           # WF/PC aperture rotation angle (degrees)
=      1                  # Computed PSF resampling factor (integer > 0)
=      0.000000           # WF/PC aperture X-axis offset (pixels)
=      0.000000           # WF/PC aperture Y-axis offset (pixels)
=      N                  # Use PM surface map? (Y or N)
=      N                  # Use SM surface map? (Y or N)
=     0.0                 # x - Jitter (milli-arcseconds)
=     0.0                 # y - Jitter (milli-arcseconds)
=      Y                  # Create  phase map file ?(Y or N)
=      N                  # Use Recovered Surface Map (Y/N/P),if Y or P then PM=SM=N.
=      N                  # Apodized the Pupil function ? (Y or N)
=      N                  # Add in random Gaussian surface (Y or N)
=      0.01               # S. Dev. of random Gaussian surface (microns).
=      993                # integer seed value for random surface generator.
=      act0.in            # Actuator file ("none" if not using)(units are um WFE).
Nact=  349                # Total number actuators in pupil.
act_cof=  39.8175         # R(r) = exp(-act_cof*r)*sin(act_cof*r+PI/4)
fullwell  = 80000.0       # Detector fullwell in electrons.
shot      = Y             # Add in shot noise (Y/N).
readnoise = 13.0          # Detector readnoise in electrons.
quant     = 4096.0        # number of quantize levels (4096 levels, 0=>not quantize).
```

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Example of Section of LEO Aperture Control File

Keywords for:

- •POLY => regular polygon apertures
- •TRIA => triangular apertures
- •RECT => rectangular apertures
- • CIRC => circular apertures
- • each aperture can have it;s own Zernikes, or can AND'ed with other sub-aps to form a segment.
- • Each set of Zernikes can have it's own center and normalization radius.

```
POLY = 1 {
        Nsides  = 6             # Number of sides of polygon
        radius  = 0.173205      # radius of inscribed polygon (meters)
        xcent   = 0.000000      # X-center of polygon (meters)
        ycent   = 0.000000      # Y-center of polygon (meters)
        theta   = 0.000000      # rotation angle of polygon (degrees))
        piston  = 0.000000      # piston error (microns-surface error)
        xtilt   = 0.000000      # tilt of mirror in x-direction (arcsec)
        ytilt   = 0.000000      # tilt of mirror in y-direction (arcsec)
        Z01     = -0.041284     # Piston (microns WFE )
        Z02     =  0.011433     # X-tilt (microns WFE )
        Z03     =  0.097507     # Y-tilt (microns WFE )
        Z04     =  0.009765     # X-Y astigmatism (microns WFE )
        Z05     =  0.097481     # Focus (microns WFE )
        Z06     =  0.131696     # 45-degree astigmatism (microns WFE )
        Z07     =  0.150290     # Trefoil (microns WFE )
        Z08     =  0.009740     # X-coma  (microns WFE )
        Z09     = -0.088725     # Y-coma  (microns WFE )
        Z10     = -0.072165     # Trefoil (microns WFE )
        Z11     = -0.100985     # (microns WFE )
        Z12     =  0.182264     # (microns WFE )
        Z13     =  0.062679     # Fourth-order spherical (microns WFE )
        apodize =  N            # anti-alias mask (Y/N).
        }

POLY = 2 {
        Nsides  =  6            # Number of sides of polygon
        radius  = 0.173205      # radius of inscribed polygon (meters)
        xcent   = 0.000000      # X-center of polygon (meters)
        ycent   = -0.306000     # Y-center of polygon (meters)
        theta   = 0.000000      # rotation angle of polygon (degrees))
        piston  = 0.000000      # piston error (microns-surface error)
        xtilt   = 0.000000      # tilt of mirror in x-direction (arcsec)
        ytilt   = 0.000000      # tilt of mirror in y-direction (arcsec)
        Z01     = -0.115865     # Piston (microns WFE )
        Z02     =  0.044346     # X-tilt (microns WFE )
        Z03     = -0.110537     # Y-tilt (microns WFE )
        Z04     =  0.020632     # X-Y astigmatism (microns WFE )
        Z05     =  0.043695     # Focus (microns WFE )
        Z06     =  0.113846     # 45-degree astigmatism (microns WFE )
        Z07     =  0.157808     # Trefoil (microns WFE )
        Z08     =  0.087005     # X-coma  (microns WFE )
        Z09     =  0.209875     # Y-coma  (microns WFE )
        Z10     = -0.004463     # Trefoil (microns WFE )
        Z11     = -0.097702     # (microns WFE )
        Z12     = -0.120061     # (microns WFE )
        Z13     = -0.013088     # Fourth-order spherical (microns WFE )
        apodize =  N            # anti-alias mask (Y/N).
        }
```

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Optical Modeling

- **(LEO) *Lyon's Electro-Optical Modeling and Analysis Software***
  - **Multiple plane *diffraction*, Fresnel, Fraunhoffer and rigorous Angular Spectrum.**
  - ***Segmented* apertures and *deformable* mirrors, influence functions, range limits, clamped and floating actuator models.**
  - **Ful- and sub-aperture *Zernike* polynomials.**
  - **power law *random surfaces*.**
  - **White noise, harmonic and low frequency *jitter models*.**
  - ***Detector effects*, MTF, charge transfer efficiency, pixelization effects, quantization error, dynamic range effects, quantum efficiency.**
  - **Gaussian and Poisson noise models.**
  - **System *radiometry* spectral filter functions, optics transmission.**
  - ***Coronagraph* capability with assortment of masks and Lyot stops.**
  - ***Scattering*, Surface Scatter, Diamond Turning, Atmosphere**
  - ***Scene Modeling* Fractal landmass, cloud and water models from LEO/ GEO and with *scan mirror* options.**
  - **Fourier Transform based *Imaging Interferometer* model.**
  - ***Inhomogenous wave propagation* finite element model (in progress)**
  - **Shack-Hartmann sensor model (in progress).**

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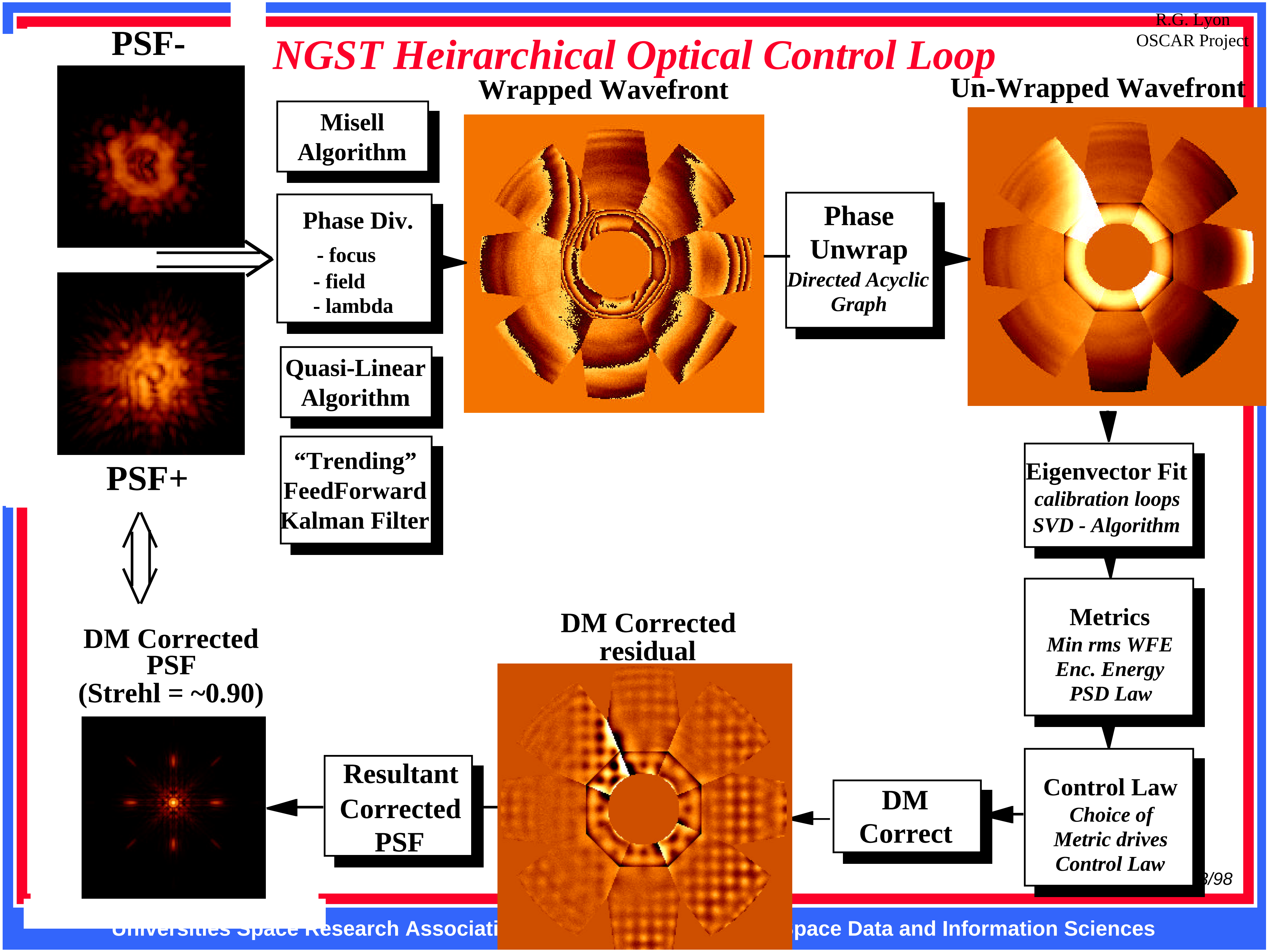
WFS Simulation and Modeling

- **Develop Wavefront Sensing Methods:**
  - **Parametric Phase Retrieval - *done***
  - **Iterative Transform Method - *done***
  - **Misell Algorithm - *done***
  - **Phase Diversity - *done***
  - **Intensity Transport Equation / Curvature Sensing - *ongoing***

- **Monte Carlo Simulation and "Shootout":**
  - **use optical model to simulate expected range of effects.**
  - **generate many different realizations (*currently ongoing*)**
  - **pass each data set through algorithms *(currently ongoing).***
  - **tabulate results.**


NGST Heirarchical Optical Control Loop
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PSF-
PSF+
Misell Algorithm
Phase Div.
- focus
- field
- lambda
Quasi-Linear Algorithm
"Trending" FeedForward Kalman Filter
Wrapped Wavefront
Phase Unwrap
Directed Acyclic Graph
Un-Wrapped Wavefront
Eigenvector Fit
calibration loops
SVD - Algorithm
Metrics
Min rms WFE
Enc. Energy
PSD Law
Control Law
Choice of
Metric drives
Control Law
DM Correct
DM Corrected residual
Resultant Corrected PSF
DM Corrected PSF
(Strehl = ~0.90)
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pace Data and Information Sciences

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Phase Retrieval Problem Statement

- From observed *Point Response Functions* find wavefront error ϕ (WFE)
- WFE gives optical surface structure.
- *Point Spread Function* is modulus squared of 2D Fourier Transform of complex pupil function. Image = convolution of PSF with object.

$$PSF(x,y;\vec{\alpha},\lambda) = \left| \frac{1}{\lambda F} \iint A(u,v)\ e^{i\phi(u,v;\vec{\alpha})}\ e^{-i2\pi(f_x u + f_y v)}\ du\,dv \right|^2$$

$$f_x = \frac{-x}{\lambda F} \quad \text{and} \quad f_y = \frac{-x}{\lambda F}$$

- The PRF is PSF integrated across spectral passband, convolved with detector spatial response and sampled.

$$PRF(x,y;\alpha) = \int PSF(x,y;\alpha,\lambda)\, S(\lambda)\, d\lambda\ **\ \mathrm{rect}\left(\frac{x}{\Delta x}\right) \mathrm{rect}\left(\frac{y}{\Delta y}\right)$$

- What's actually measured is given by:

$$M(x,y;\alpha,\ flux, A,B,C) = flux * PRF(x,y;\alpha) + A*x + B*y + C + \eta(x,y)$$

- Requires complex nonlinear iterative algorithms to find $\varphi(u,v)$ from M(x,y,α,flux,A,B,C)

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Control Precision vs. rms WFE

- **Utilized LEO to generate 400 PSFs, 4 each at 100 realizations of WFE from 0 - 2.5λ rms.**
  - Full aperture Zernikes, Sub-aperture Zernikes, segment piston/tip/tilt
  - finite spectral bandpass (λ=0.6328,Δλ=10nm)
  - detector and actuator effects.
- **Passed each through:**
  - 4 PSF Misell,
  - phase unwrapping,
  - DM control, DM control with limits,
  - DM+PM control.
- **Tabulated output precisions vs. rms WFE for each case.**
- **WFS precision is λ/23 +/- λ/52 rms**
- **Control with range limited DM+PM ~λ/10**
- **RSS of Sensing and Control errors is ~λ/9**
- **Error budget is ~λ/4.43 {E. Young 9/23/97 DCATT Peer Rev}.**

Wavefront Sensing Precision

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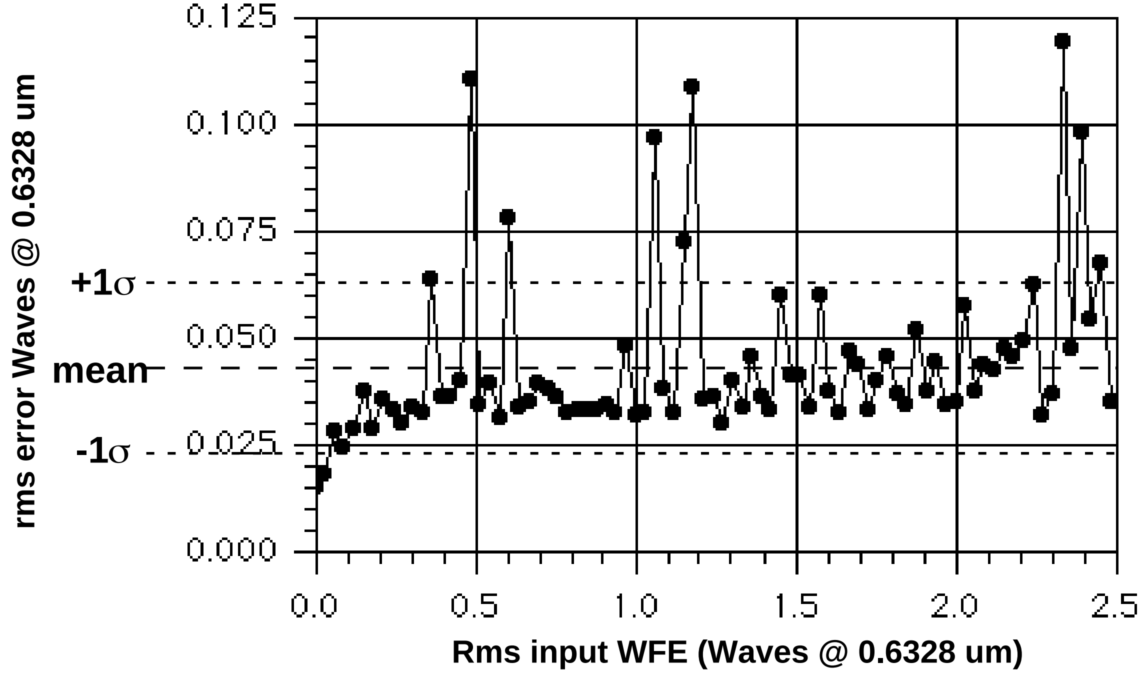

- Wavefront sensing precision is $\boxed{\lambda/23 +/- \lambda/52}$ over range {0 - 2.5λ}.
- Anomolies caused by phase unwrapping problems.

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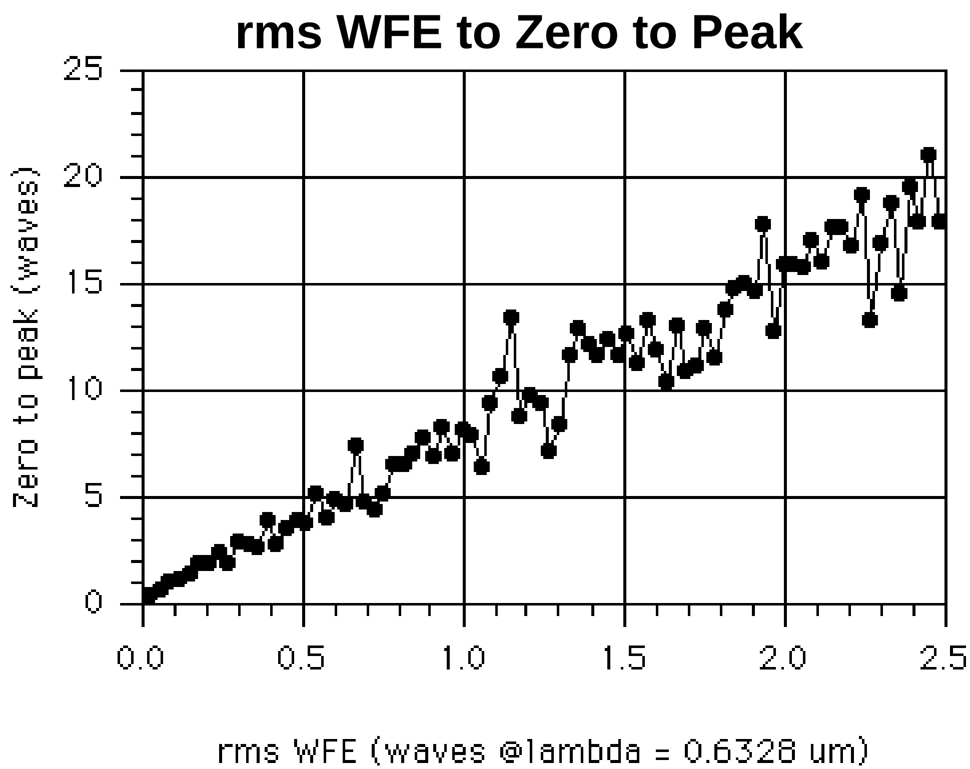
Phase Unwrapping



slope ~7.5 waves/rms wave
phase unwrap **for > 0.15 waves rms**

- **Number of Phase Unwrapping Methods Explored**
- **Problems occur for:**
  - **Large slopes => unresolved edges**
  - **Jitter => "*Branch Points*"**
  - **Low SNR => poor "fringe edge"**
- **Need diagnostic to tell *if needed* and *if failed***

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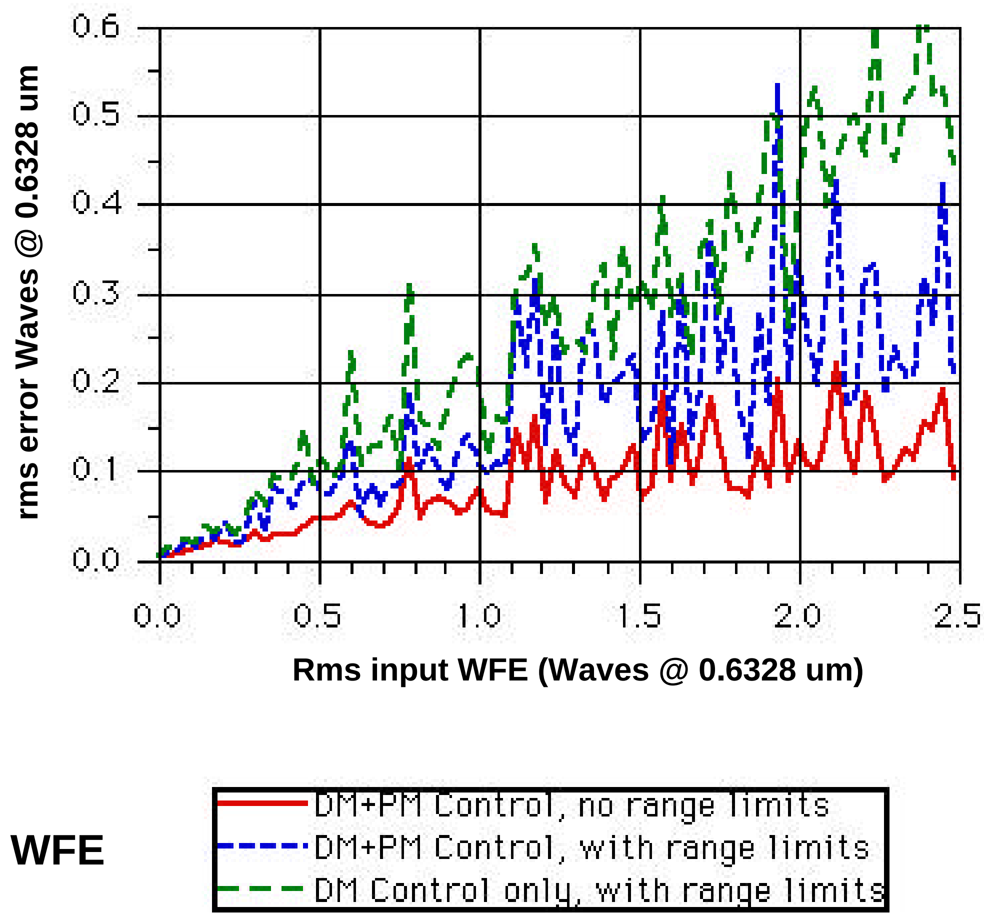
DM and PM Control vs rms WFE



- **Over error budgeted range {0 - 1λ rms}**

  DM+PM controls < λ/10

- **Error grows linearly with rms WFE**

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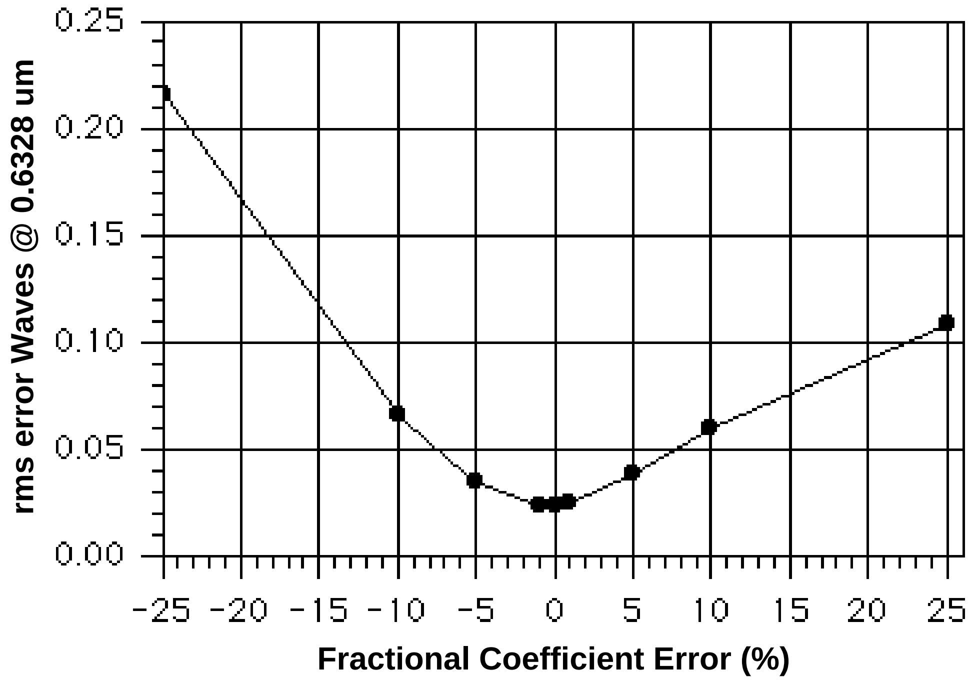
Influence Function Sensitivity



- **Influence function model for DM from Dave Redding:**

$$R(r) = e^{-Ar}\cos(Ar)$$

- **"A" varied over +/- 25% from nominal**
- **Input WFE = 0.25 waves rms (lambda = 0.6328 um)**

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In-Situ Calibration/System Identification

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- Drift in Actuator Influence Functions lowers achievable *image quality*.
- Changes due to
  - Gravity Release
  - Material Properties Drift
  - Thermal Drift/Gradients
  - Human Error
- Influence functions can be updated on-orbit:

$$\tilde{\mathbf{R}}_{(n+1)} = \tilde{\mathbf{R}}_{(n)} + \left[\mathbf{w}^{(n+1)} - \tilde{\mathbf{R}}_{(n)}\mathbf{a}^{(n+1)}\right]\mathbf{K}_{(n+1)}$$

- **w** is an observed wavefront, **R** the influence function matrix

  a the vector of actuator positions with $\mathbf{w} = \mathbf{R}\mathbf{a} + \varepsilon$

  and: $\mathbf{P}_{(n)} = (\mathbf{A}_{(n)}\mathbf{A}^{\mathrm{T}}_{(n)})^{-1}$

$$\mathbf{K}_{(n+1)} = \frac{\mathbf{a}^{\mathrm{T}(n+1)}\mathbf{P}_{(n)}}{1 + \mathbf{a}^{\mathrm{T}(n+1)}\mathbf{P}_{(n)}\mathbf{a}^{(n+1)}} \qquad \mathbf{P}_{(n+1)} = \mathbf{P}_{(n)} - \frac{\mathbf{P}_{(n)}\mathbf{a}^{(n+1)}\mathbf{a}^{\mathrm{T}(n+1)}\mathbf{P}_{(n)}}{1 + \mathbf{a}^{\mathrm{T}(n+1)}\mathbf{P}_{(n)}\mathbf{a}^{(n+1)}}$$

- 256K wavefront points 375 actuators, => 197MFLOP
  For 2700 actuators this expands to 1.43 GFLOP

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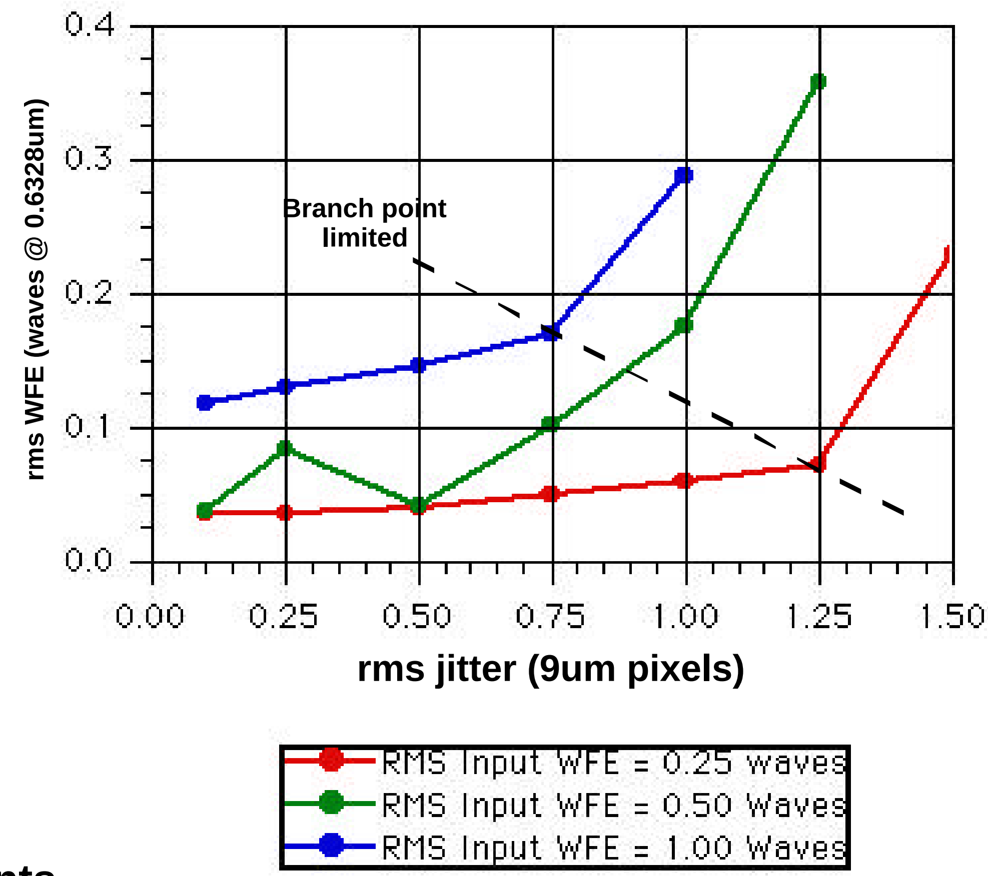
WFS Precision due to Jitter

- Jitter model is non-deterministic.
- Low-pass filter on OTF:

$$\langle H(f_x, f_y)\rangle = e^{-\left(\sigma_x^2 f_x^2 + \sigma_y^2 f_y^2\right)}$$

- x-rms <=> y-rms
- Hi-FI models possible.
- effect is generation of "unphysical" branch points.
- Branch points cause errors in phase unwrapping.
- Useful as diagnostic ?
- Number of branch points imply severity of jitter.
- Jitter *deconvolution* possible ?
- Metric would be residual branch points.



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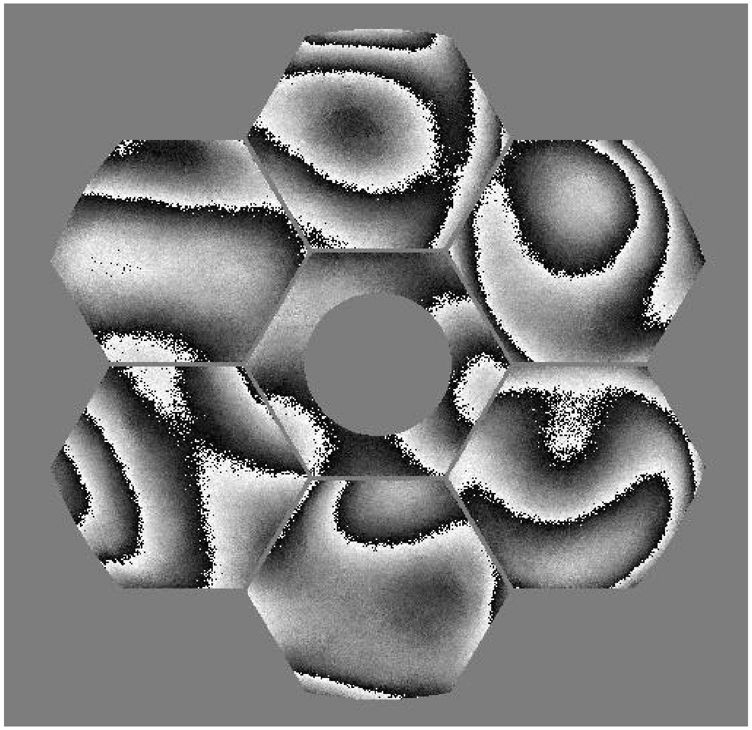
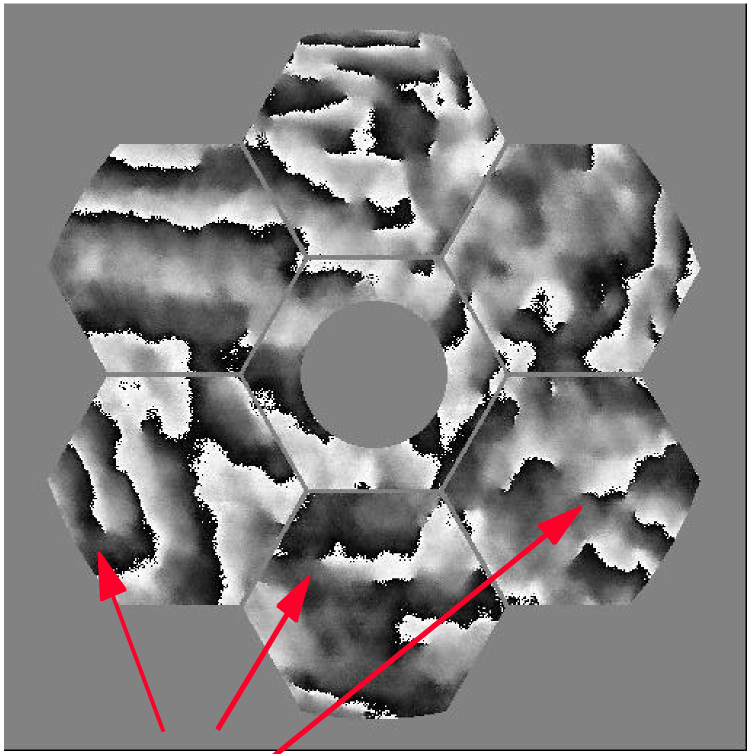
Jitter Induced Branch Points



WFE = 1.00 waves rms
Jitter = .1 pixel rms (9 um)



Jitter Induced
Branch Points

WFE = 1.00 waves rms
Jitter = 1 pixel rms (9 um)

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Allowable Jitter strongly correlated with WFE.
Jitter makes phase unwrapping tough.

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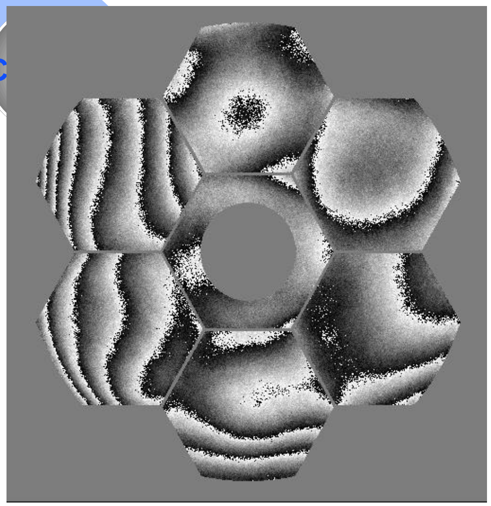
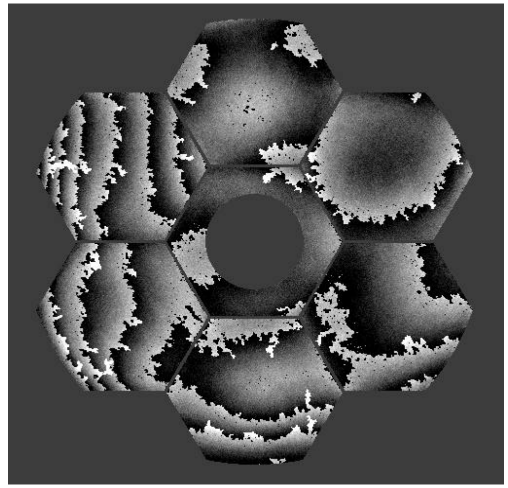
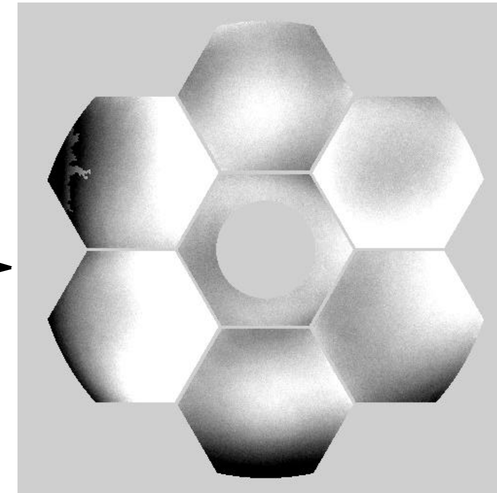


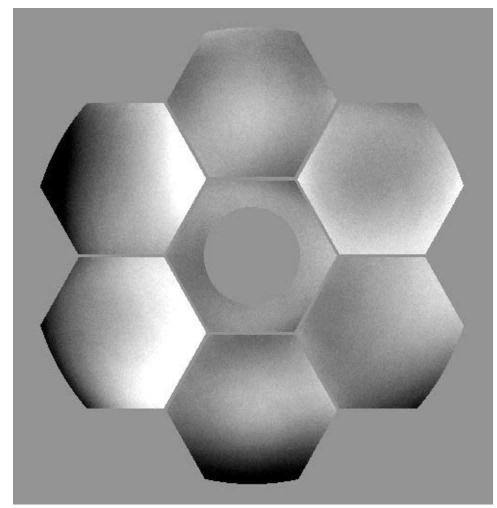
4 PSF Misell Algorithm Solution
Optical, Detector effects
~100 iterations, l=.6328um dl=100 Ang



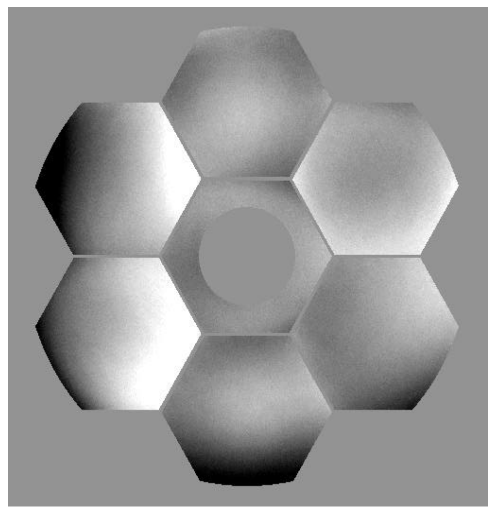
Phase Unwrap Preprocessor
(lowers number of regions)



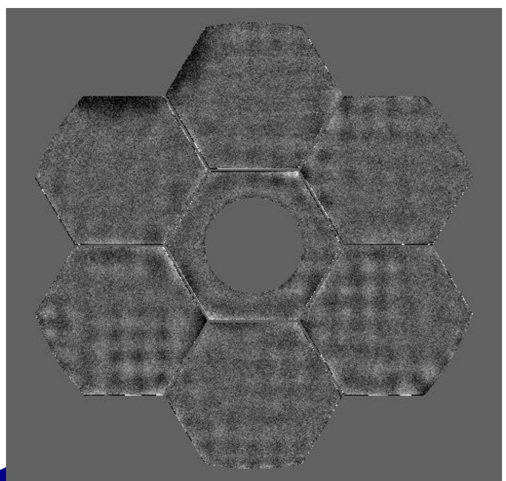
Swipe 1 of DAG
phase unwrapping



Swipe 2 of DAG
phase unwrapping



Best fit Wavefront
Both DM and PM Control
min{rms} metric



Residual WFE
Both DM and PM Control
rms=l/12,max-min=1.3 l

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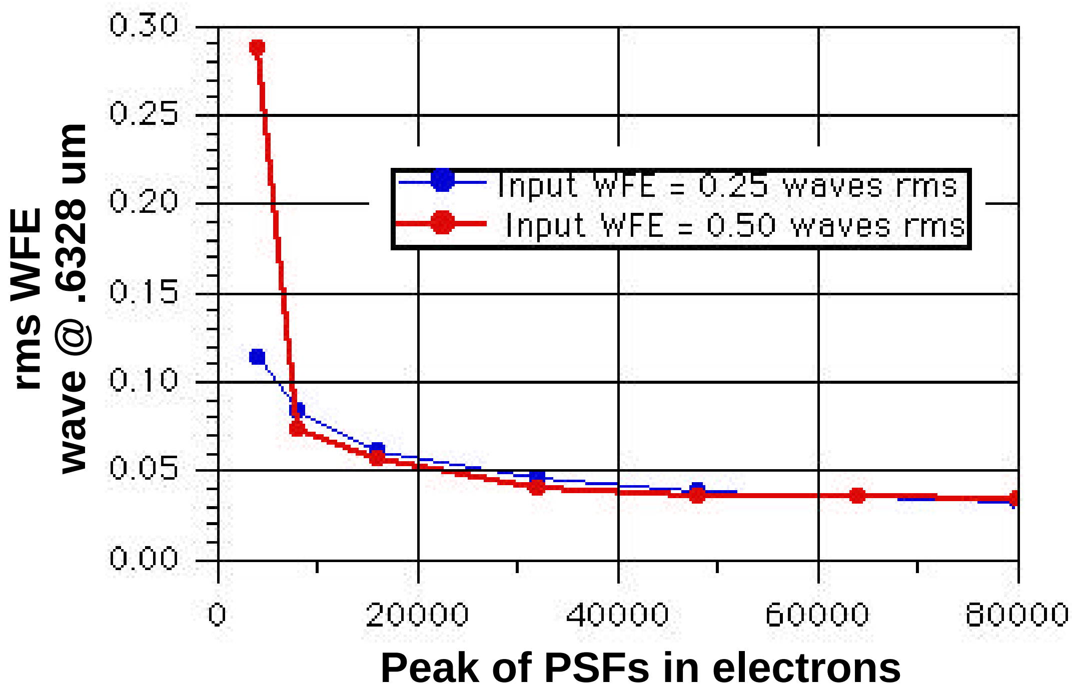
WFS Precision vs. SNR

- Utilized LEO to generate sequence of different SNR PSFs,
- 7 sets at σ=0.25λ rms, and 7 sets at σ=0.25λ rms, 4 PSFs/ realization.
- Passed each through 4 PSF Misell with phase unwrapping.
- Tabulated output precisions vs. SNR
- RMS output error was < $\lambda/20$ > 20,000 electrons.
- Errors due to: phase edge loss and increased phase noise



KAF1600 chip
readnoise 13e rms.
80,000e full well.
12 bit quantization.
9 micron pixels

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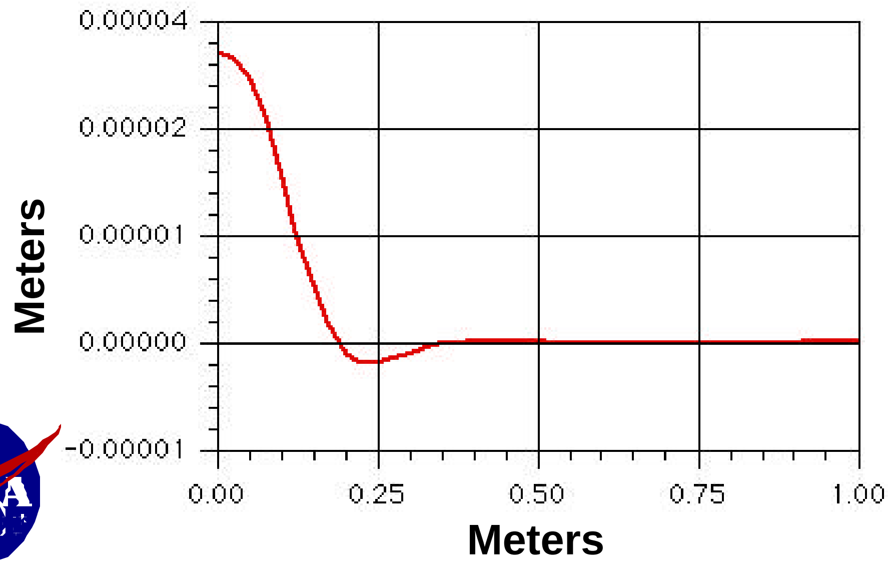
Future Work:

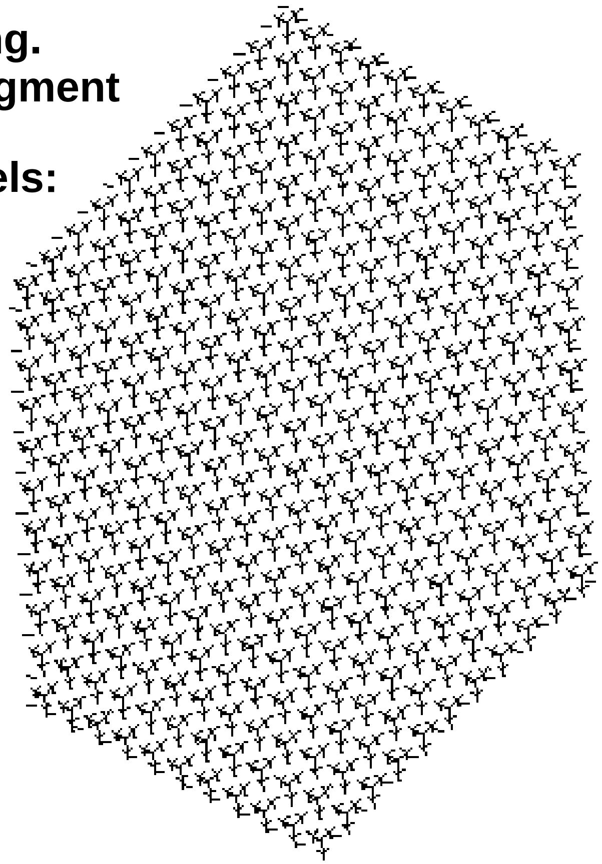
Integration of U. of A. Mirror into Model

- Obtained influence functions model.
- Use linear systems approach to actuator fitting.
- Each segments actuators effects only that segment in contrast to DM model.
- Thus becomes 7 seperate least squares models:

$$\mathbf{w}^{(j)} = \mathbf{R}^{(j)}\mathbf{a}^{(j)} \quad j = 1,\ldots,7$$

$$\mathbf{a}^{(j)} = \left(\mathbf{R}^{(j)\mathbf{T}}\mathbf{R}^{(j)}\right)^{-1}\mathbf{R}^{(j)\mathbf{T}}\mathbf{w}^{(j)}$$





- 3 meters flat to flat
- 394 actuators total
- 331 load spreaders + 63 edge

Model compliments of
L. Craig, A. Kissel, G. Mosier, D. Redding

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Major Results of models for DCATT to Date

Simulations show error budget can be met for DCATT Fine Figure Control.

Over budgeted range 0 - 1 λ rms input WFE for DCATT

WFS	~λ/23
DM+PM Control	< λ/10
Jitter	< λ/8 (0.25 rms jitter)
SNR	~ λ/10 (Fullwell > 20000, SNR > 62
σ (RSS)	~λ/5.2
σ (error budget)	λ/4.43

- **Doesn’t include stray light, diamond turning or turbulence.**
- **WFS Precision strongly correlated with Jitter.**
- **Phase unwrapping needs to be addressed in more detail.**
- **SNR doesn’t appear to be a problem.**
- **Phase Retrieval can be used over much large input WFE range.**

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Summary

- **Developed Hi-Fi computer models for DCATT and NGST optics.**
- **Developed WFS and OCS loop software.**
  - developed on MasPar MP2, in a superset of “C”.
  - currently being converted to “C” with MPI.
  - deliver NGST baseline WFE/OCS to HPCC/REE December 1998 (Release 1.0), 2nd release in December 1999.
- **Verified DCATT WFS/OCS error budget.**
- **Compartive WFS (Phase Ret/Div, Shack-Hartmann).**
  - Report will be available by January 1999.

Future Work

- **Integrate U. of A. mirror concept into NGST models.**
- **“Quasi-Linear” WFS, In-situ science obs WFS.**
- **In-situ system calibration (aka system identification).**
- **Hi-density actuators / WFS for ISIM coronagraph.**
- **Verify models and algorithms with “real” DCATT data.**
- **Use “real” DCATT results for optimal NGST WFS/OCS design.**